Ethylene based on woody biomass—what are environmental key issues of a possible future Swedish production on industrial scale

**Christin Liptow · Anne-Marie Tillman · Matty Janssen ·
Ola Wallberg · Glenn A. Taylor**

Abstract

Purpose In order to reduce its environmental impact, the chemical industry no longer produces base chemicals such as ethylene, solely from fossil, but also from biomass-based feedstocks. However, a biomass option suitable for one region might not be as suitable for another region due to, e.g., long transport and the related environmental. Therefore, local biomass alternatives and the environmental impact related to the production of chemicals from these alternatives need to be investigated. This study assesses the environmental impact of producing ethylene from Swedish wood ethanol.

Methods The study was conducted following the methodology of life cycle assessment. The life cycle was assessed using a cradle-to-gate perspective for the production of 50,000 tonnes ethylene/year for the impact categories global warming, acidification (ACP), photochemical ozone creation, and eutrophication (EP).

Results and discussion The production of enzymes used during the life cycle had a significant effect on all investigated impacts. However, reduced consumption of enzyme product, which could possibly be realized considering the rapid development of enzymes, lowered the overall environmental impact of the ethylene. Another approach could be to use alternative hydrolyzing agents. However, little information on their environmental impact is available. An additional key contributor, with regard to ACP, EP, and POCP, was the ethanol production. Therefore, further improvements with regard to the process' design may have beneficial effects on its environmental impact.

Conclusions The study assessed the environmental impact of wood ethylene and pointed to several directions for improvements, such as improved enzyme production and reduced consumption of enzyme products. Moreover, the analysis showed that further investigations into other process options and increase of ethylene production from biomass are worth continued research.

Keywords Biomass-based chemicals · Ethylene · Life cycle assessment · Wood ethanol

C. Liptow (✉) · A.-M. Tillman · M. Janssen
Division of Environmental Systems Analysis, Chalmers University of Technology, 412 96 Göteborg, Sweden
e-mail: liptow@chalmers.se

O. Wallberg
Department of Chemical Engineering, Lund University, 221 00 Lund, Sweden

G. A. Taylor
Department of Chemical and Nuclear Engineering, University of New Mexico, Albuquerque, NM 87131, USA

1 Introduction

1.1 General introduction

In recent years, we have seen a significant development of biofuels in the transport sector, aiming at the reduced consumption of finite fossil oil and the related release of emissions. For example, biodiesel production increased from 3.4 million tonnes globally in 2005 to 18.1 million tonnes in 2011 (Naumann 2011). In addition, bioethanol production increased from 24.7 million tonnes globally to 69.7 million tonnes (Naumann 2011). And although the transport sector is one of the major consumers of oil (in 2009 transport accounted for 61.7 % of the world's oil consumption) (International Energy Agency (IEA) 2011), there are also other sectors operating on fossil resources such as the chemical industry. The latter accounts for approximately 8 % of the global oil consumption (Gottschlich 2004) and thus has potential for reducing the consumption of fossil resources and the release of related emissions.

In fact, the chemical industry is aware of this potential and has already started using biomass-based feedstocks for selective production processes. For example, the Brazilian company Braskem uses sugarcane ethanol in order to produce the base chemical ethylene (Braskem 2011; accessed September 11, 2011). However, although being renewable, several studies have shown that sugarcane ethanol can have considerable indirect environmental consequences, which could negatively influence its overall climate change mitigation effect. For example, Gao et al. (2011) concluded that indirect land use change (ILUC) effects for biofuels such as Brazilian sugarcane ethanol is an issue that cannot to be neglected in assessments and Lapola et al. (2010) found that emissions from ILUC could add another 40 years to the carbon payback time of sugarcane ethanol.

Another factor needed to be considered with sugarcane ethanol, especially from a European perspective, is the absence of close-by, large-scale production areas of sugarcane leading to long transport distances, and related negative environmental impact (Liptow and Tillman 2012). For these reasons local European feedstocks, available in abundant quantities, are of interest. A possible solution currently being discussed and developed is the use of lignocellulosic crops or by-products. This approach is particularly interesting for Northern European countries, such as Sweden, since the latter not only has a vast forestry industry with all its by-products ("one of the major forest industry globally" (Swedish Forest Industries Federation 2010)) but also a petrochemical industrial cluster, largely based on ethylene. In addition, Sweden has an ethanol demo-plant investigating the conversion of woody biomass to ethanol (SEKAB accessed March, 26th 2012). Therefore, Swedish production of ethylene from wood ethanol is a conceivable option in 5 to 10 years time. It is a range that leaves room for improvements regarding the environmental impact of such a production chain before an actual industrial scale implementation. The latter can be supported by environmental assessments, such as life cycle assessment, that assess possible scenarios for the production of ethylene from Swedish wood ethanol and identify related environmental key contributors (life cycle activities contributing significantly to the environmental impact).

This study assesses one such scenario using life cycle assessment (LCA) for the production of 50,000 tonnes/year (t/year) ethylene from wood-based ethanol via enzymatic hydrolysis and fermentation. The capacity was based on communications with industrial actors, which stated that to be of industrial relevance for downstream applications a quantity of at least 50,000 t ethylene/year would be needed.

The focus of the assessment is on the identification of possible environmental key contributors and hence areas where further development is needed, from an environmental point of view.

The information provided by the study is of significant importance for the further development and implementation of biomass-based ethylene in Sweden and regions with comparable conditions.

1.2 Selection of feedstock option

The study aims at assessing a possible near-term (5 to 10 years) production of renewable ethylene in Sweden based on wood ethanol. For this purpose, a scenario was constructed which aims at representing a potentially feasible situation in a 5- to 10-year time frame.

When constructing the scenario, consideration was given to possible scale of production in relation to feedstock potentials. However, the competing uses for biomass and related possible market development were not analyzed.

The following factors were considered for the selection of a feedstock for the scenario:

- The feedstock needs to be available in sufficient quantities. "Sufficient" in this study means to cover the production of 50,000 tonnes ethylene/year.
- The feedstock needs to be readily available in terms of an already existing production infrastructure.
- The feedstock needs to be as homogenous as possible in order to enable a consistent ethanol yield.

The characteristics of three possible candidate feedstocks are presented in the selection scheme in Table 1. It was concluded that, though all candidates could fulfill the quantity criterion[1], sawmill residues have the best perspective with regard to accessibility and homogeneity. For this reason, sawmill residues and in particular sawmill chips, which are the biggest volume fraction of these residues (Andersson 1996), were used in this study to assess the production of biomass-based ethylene in Sweden.

2 Materials and methods

2.1 Goal and scope

The purpose of this LCA was to assess the environmental impact of a possible future-state in which ethylene is produced from sawmill chips at an industrially relevant scale, with focus on the identification of possible environmental key contributors. The route studied was via fermentation to ethanol followed by dehydration to ethylene. The assessment followed the ISO standard for LCA (2006) and an

---

[1] Wood needed to produce 50,000 tonnes ethylene is $\sim 4.5 \times 10^5$ tonnes (dry matter content 50 %) (unallocated).

Table 1 Data considered for selection of feedstock

	Tops and branches	Wood from pre-commercial thinning	Sawmill residues
Capacity	Harvested in 2009 115,095 ha ~4×10^6 tonnes DM[a] (Skogsstyrelsen 2010), (personal communication with H. Eriksson, Skogsstyrelsen, October 2010)	Potential 5×10^6 tonnes DM/annually (Nordfjell et al. 2008)	Produced in 2008 (for pulp and wood panel industry) 11.6×10^6 m^{3}f ub ~5×10^6 tonnes DM[b] (Skogsstyrelsen 2010; Lehtikangas 1999)
Accessibility	Can be harvested together with commercial harvesting (personal communication with D. Athanassiadis, Dept. of Forest Resource Management at the Swedish University of Agricultural Science, Umeå, Sweden, December 2010)	Need for extra infrastructure; not located together with commercial harvested wood (personal communication with D. Athanassiadis, Dept. of Forest Resource Management at the Swedish University of Agricultural Science, Umeå, Sweden, December 2010)	Readily accessible at sawmills
Homogeneity	Very inhomogeneous (personal communication with D. Athanassiadis, Dept. of Forest Resource Management at the Swedish University of Agricultural Science, Umeå, Sweden, December 2010)	Very inhomogeneous (personal communication with D. Athanassiadis, Dept. of Forest Resource Management at the Swedish University of Agricultural Science, Umeå, Sweden, December 2010)	Relatively homogenous in comparison to the other two options (personal communication with D. Athanassiadis, Dept. of Forest Resource Management at the Swedish University of Agricultural Science, Umeå, Sweden, December 2010)

[a] Extraction rate 30 DM tonne/ha (Eriksson); *DM* dry matter

[b] m^3 f ub = cubic meters solid volume excluding bark; DM density 410 kg/m3 (Lehtikangas 1999)

attributional LCA approach was used, implying average electricity supply data and allocation through partitioning following Tillman (2000). A reference group consisting of stakeholders along the life cycle followed and reviewed the assessment.

2.1.1 Ethanol production process

The ethanol production process assessed here, simultaneous saccharification and fermentation (SSF) after enzymatic hydrolysis of lignocellulosic biomass, has not yet been implemented on an industrial scale. However, pilot plants do exist, and the implementation could take place within the next 5 to 10 years. This time frame allows for further developments of the enzyme products used in the process, such as increasing their activity and consequently reduce their consumption. For example, the latest generation of cellulase (enzyme) products is 50 % more efficient than the previous generation, which was launched only 2 years ago (Novozymes 2012; accessed February 23, 2012). Another factor that could lead to optimizing (minimizing) the consumption of enzyme product is economic viability. It could lead development to reduce the consumption even further than what is currently investigated. Reductions about five times and more due to overall process economics (personal communication with Johan Börjesson, Novozymes, Bagsvaerd, Denmark, July 2011) might occur. Following these considerations, the ethanol process was assessed with

enzyme product consumptions based on current product specifications (lower and higher end activity) as well as possible future consumptions (the latter were estimated by lowering the current consumptions by a factor eight for the lower end activity product and by six times for the higher end activity product). Apart from the difference in enzyme consumption, the scenario used for the assessment was as follows:

Three ethanol plants surrounded by several sawmills that are located in the middle, and at the east coast of Sweden (Fig. 1) were assumed to be required to supply the ethanol needed to operate a central ethylene plant located in Stenungsund (Sweden). Multiple ethanol plants were assumed here, since several sawmills are needed to supply the necessary amount of sawmill chips. The construction of several smaller ethanol plants may, therefore, be more likely than one big central plant in order to, e.g., reduce transportation costs. The ethanol plants were assumed to be located close to sawmills that are relatively far-off from other customers like, e.g., pulp and paper mills. The ethylene plant was assumed to be located in Stenungsund (Sweden), since Stenungsund is the central chemical production site in Sweden.

2.1.2 Data sources

For all steps from forestry to sawmill chips production, current Swedish data were used, assuming no significant
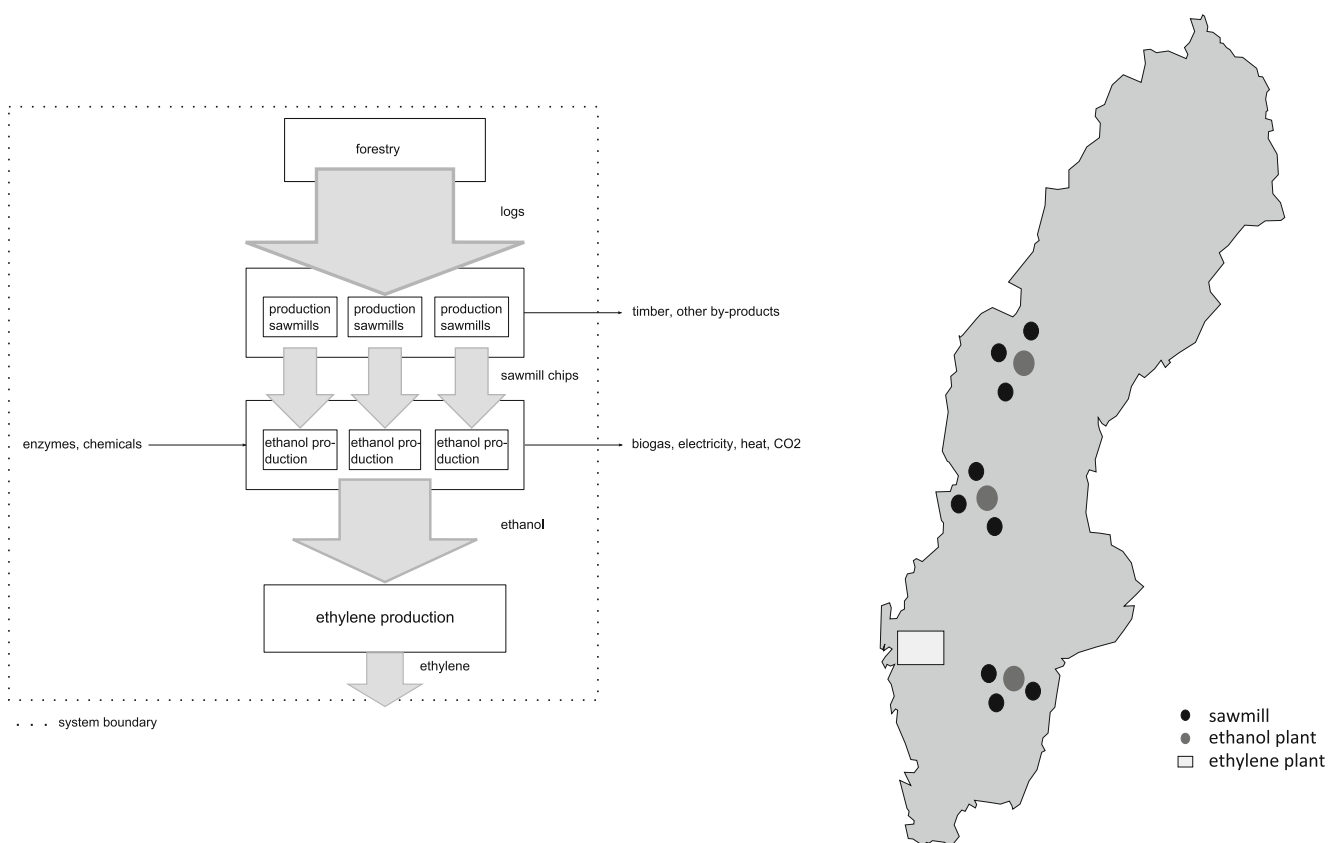
Fig. 1 Life cycle of Swedish wood ethanol-based ethylene; transport omitted from figure for clarity reasons but included in the assessment

changes in the coming 5 to 10 years. Due to the absence of industrial scale data for the ethanol production, process data was generated with the process simulation software Aspen Plus®. Producer data (personal communication with Nielsen, A.M., Novozymes, Bagsvaerd, Denmark, May–June 2011) was used for the production of the enzymes. Since the data provided were too highly aggregated to derive data distinguishing between current and future production, the same production impact data were used for the current and the potential future scenarios. For the chemicals and nutrients (SO_2, molasses, $(NH_4)_2HPO_4$, H_3PO_4, NH_3) consumed during the ethanol production, data from the LCA software SimaPro 7.2 (Ecoinvent v 2. 2.) (Pre Consultants 2011) were applied. After being verified with the process simulator Aspen Hysys® (Liptow and Tillman 2009) the dehydration of the ethanol to ethylene was assessed using literature data (Kochar et al. 1981; Barrocas and Lacerda 2007). Regarding production of the electricity consumed by the different processes in the life cycle, data from the current average Swedish electricity supply were used as stated in Börjesson et al. (2010), assuming no major changes in the mix for the time frame assessed. This was based on projections published by the IEA (International Energy Agency) (2008).

2.1.3 Impacts assessed

The following potential environmental impacts were assessed:

–   Global warming (only CO_2 from fossil sources was accounted for, biogenic CO_2 was considered carbon neutral and thus not accounted for)
–   Acidification
–   Eutrophication
–   Photochemical ozone creation

The functional unit is 50,000 t/year ethylene at the gate of the production plant.

2.2 Inventory

2.2.1 Timber production (forestry)

The production of the timber was assessed using data for an averaged 1 m3 s.u.b. (cubic meter solid under bark) produced in Sweden according to Berg and Lindholm (2005) and Lindholm (2006). The data (Table 2) includes all operations from seedling production, site preparation, regeneration, cleaning and logging operations as well as the delivery of the timber to the mills (Berg and Lindholm

Table 2 Inventory for forestry

	Quantity	References
Input		
Primary energy	183.90 MJ/m^{3}s.u.b.[a]	(Lindholm 2006)
Product output		
Round wood	1 m^{3}s.u.b.	(Lindholm 2006)
Emission including upstream for energy carriers		
CO_2	12.52 kg/m^{3}s.u.b.	(Lindholm 2006)
NOx	0.12 kg/m^{3}s.u.b.	(Berg and Lindholm 2005)
SO_2	4.9×10^{-4}kg/m^{3}s.u.b.	(Berg and Lindholm 2005)
HC	0.01 kg/m3s.u.b.	(Berg and Lindholm 2005)
CO	0.03 kg/m^{3}s.u.b.	(Berg and Lindholm 2005)
CH_4	1.0×10^{-3}kg/m^{3}s.u.b.	(Berg and Lindholm 2005)
N_2O	$8.8 \times 10^{*-4}$kg/m^{3}s.u.b.	(Berg and Lindholm 2005)

[a] *s.u.b.* solid under bark

2005). Berg and Lindholm (2005) also consider the production of all energy carriers, ancillary materials and nitrogen production as well as nitrogen leakage. No further chemicals such as pesticides or phosphorous and potassium fertilizer are considered, since they are commonly not applied in Swedish forestry (González-García et al. 2009).

2.2.2 Sawmill chips production

Sawmills consume both heat and electricity. However, the heat is used to dry the timber, a process which the sawmill chips do not undergo (Andersson 1996). For this reason, no heat was allocated to the sawmill chips.

The electricity consumption of the mills was estimated at 95 kWh$_{el}$/m^3 sawn timber based on data from Naturvårdsverket (Naturvårdsverket Swedish EPA 2010). The emissions resulting from the production of this electricity were partitioned between the sawmill chips and the other products of the mills based on price (other products are: sawn timber, dry chips, saw dust and bark and shavings; dry chips and bark and shavings were assumed to have the same price as sawmill chips) (see Table 3 for more details).

2.2.3 Ethanol production

The conversion of the sawmill chips to ethanol via fermentation and all related processes was simulated in Aspen Plus®. This simulation delivered the on-site emission data

for the process. The fermentation also consumed enzymes and various nutrients produced off-site. The environmental impact of the latter was assessed using data from Ecoinvent v.2.2, SimaPro 7.2 (PRé Consultants 2011).

Since the production of the ethanol results in various co-products, the overall environmental impact of the process was partitioned on a price basis between the different products (Table 4).

2.2.4 Process simulation model for ethanol production

The process model for the ethanol fermentation and all related processes was set up in Aspen Plus® (note, the model used is only one out of various possible process configurations). A full model description can be found in Barta et al. (2010a; b) and Sassner et al. (2008).

Each modeled plant has a capacity of 25,000 kg dry chips/h (200,000 tonnes dry chips/year) (Barta et al. 2010a). The process sequence starts with SO_2-catalyzed steam pretreatment, followed by SSF. The latter consists of enzymatic hydrolysis (enzyme dosage 221×10^6 filter paper unit (FPU)/h^2) and fermentation with baker's yeast. The resulting fermentation broth (ethanol concentration 3.5 % (wt)) is distilled, delivering ethanol (top product of distillation) and stillage (bottom product of distillation). The ethanol is further purified to 99.8 % (wt)[3] in molecular sieves (Barta et al. 2010b). The stillage is digested anaerobically, producing biogas, followed by an aerobic digestion of the remnant, which results in sludge and waste water. The latter is treated with ozone and recycled into the process.

The energy demand of the processes is covered by combusting part of the produced biogas and the sludge coming from the aerobic digestion (Barta et al. 2010b).

2.2.5 Enzyme production

For the enzyme production, the producer provided data as aggregated cradle-to-gate impact data (personal communication

---

[2] One filter paper unit for cellulase enzymes according to Ferreira et al. (2009) is "the amount of enzyme that releases 1 micromole glucose per minute during hydrolysis reaction" and can be used to describe the activity of the enzyme. The enzyme product assessed in this study, however, does not only contain the enzyme but also some formulation materials. For this reason 1 g of enzyme product does not necessarily equal 1 g of enzyme rather it may vary for different products and product generations. The stated FPU dosage was, therefore, only used to calculate the enzyme product consumption for the current scenarios, since only data for current FPU/g enzyme product were available. For the future consumption scenarios, however, simplified estimates of possible future enzyme product consumptions were made, without the intention to project.

[3] This high purity is not necessary for the production of ethylene. However, the model was set up to simulate production of biofuels, which require this high concentration.

Table 3 Sawmill inventory data

Input	Quantity		References
Electricity	95kWh$_{el}$ /m^3 sawn timber[a] (weighted average)		(Naturvårdsverket Swedish 2010)
Round wood	2.1 m^3 s.u.b./m^3 sawn timber		(Skogsstyrelsen 2010)
Product output	**Sold quantities**	**Price**	**References**
Sawn timber	100,000 m^3/year	1,886 SEK/m^3	(Andersson 1996; Skogsstyrelsen 2010)
Sawmill chips	170,000 m^{3}s[b]/year	451 SEK/m^{3}f ub	(Andersson 1996; Skogsstyrelsen 2010)
Dry chips	20,000 m^{3}s/year		
Saw dust	64,400 m^{3}s/year	1,176 SEK/ m^{3}f ub	(Andersson 1996; Skogsstyrelsen 2010)
Bark/shaving	4,200 m^{3}s/year		

[a] kWh_{el} kilowatt hour electricity
[b] m^3s m^3 stjälpt (loose volume); conversion factor m^{3}s to m^3 f ub= 0.37 (personal communication with S. Joshi at Swedish Forestry Agency, Jönköping, Sweden, January, 23rd 2013)

with Nielsen, A.M., Novozymes, Bagsvaerd, Denmark, May–June 2011). The data represent Danish production under natural gas electricity supply for the global warming potential (GWP) and US production data under natural gas electricity supply for the acidification potential (ACP), photochemical ozone creation potential (POCP) and eutrophication potential (EP) (see Table 5 for data). Due to their high level of aggregation, data could not be adapted to represent production under average Danish electricity supply. This may have resulted in slight underestimate for the investigated impacts, though the trend in results was expected to be comparable to Danish production under average electricity.

2.2.6 Ethylene production

The production of the ethylene from ethanol was assessed using data from Liptow and Tillman (2012) (Table 6). In this study, though, the electricity supply was taken as Swedish average electricity (Börjesson et al. 2010).

2.2.7 Transport activities

It was assumed that the distance ranges were between 30 and 50 km for the transport of the sawmill chips to the ethanol plants. The means of transport assessed was trucks with semitrailers according to the Network for Transport and the Environment (NTM 2011; accessed April 6, 2011) (see Table 7 for transport emissions).

For the fermentation process, it was assumed that enzymes are delivered by Novozymes, Kalundborg (Denmark) (distances between Kalundborg and the three ethanol plants: 490, 850, and 1,200 km). The nutrients consumed were assumed to originate from Yara in Köping (Sweden), apart from the molasses that was assumed to be delivered by Nordic Sugar AB (Malmö, Sweden). The resulting transport distances for the nutrients are 250 km, 200 km and 470 km. For the molasses transport the distances to the ethanol plants are: 350, 710, and 1060 km. All transport was assessed using data from NTM (NTM 2011; accessed April 6, 2011).

Table 4 Inventory data for ethanol production

Input	Quantity	Process emissions	
NH$_3$ (25 %)	882 kg/h	NO$_x$	17,99 kg/h
H$_3$PO$_4$ (50 %)	58 kg/h	SO$_2$	16,65 kg/h
(NH$_4$)$_2$HPO$_4$	74 kg/h	CO	5.93×10^{-4}kg/h
Molasses	886 kg/h	N$_2$O	1.41×10^{-3}kg/h
Enzymes	221×10^6FPU/h		
SO$_2$[a]	641 kg/h		
Chips (50 % DM))	25,000 kg/h		
MgSO$_4$[a]	4 kg/h		
Product output	**Quantity**	**Price**	**Reference**
Electricity	5.4 MW	855 SEK/MWh	(Statistics Sweden accessed March 7, Statistics 2011)
District heating	31.1 MW	747 SEK/MWh	(Svensk Fjärrvärme (Swedish district heating) (2011))
Ethanol	6,177 l/h	5.5 SEK/l	
CO$_2$	5,153 kg/h	0.03 SEK/kg	
Biogas	1,906 kg/h	11.7 SEK/m^3	(E-On accessed March 7 (2011)

[a] Data with regard to the environmental impact of magnesium sulfate (MgSO$_4$) production were not found. Therefore, production of MgSO$_4$ could not be considered in the assessment. Data for the production of SO$_2$ were only found expressed as CO$_2$ eq. Therefore, SO$_2$ production is only considered under GWP.

Table 5 Life cycle data for enzyme production

Impact	Potential	Unit
GWP[a]	9,000.0	g CO_2 eq/kg enzyme product
ACP[b]	56.0	g SO_2 eq/kg enzyme product
POCP[c]	3.8	g ethylene eq/kg enzyme product
EP[d]	15.0	g PO_4 eq/kg enzyme product
Fossil energy	120	MJ/kg enzyme product

[a] *GWP* global warming potential

[b] *ACP* acidification potential

[c] *POCP* photochemical ozone creation potential

[d] *EP* eutrophication potential

Data from NTM (2011) (accessed April 6, 2011) were also used for the transport of the ethanol from the different plants to the ethylene production site in Stenungsund (Sweden). Trucks with semitrailers were assumed to cover the transports of 290 km, 430 km and 800 km.

3 Results and discussion

The aim of this study was to assess the environmental impact of an ethylene production from Swedish wood ethanol via fermentation in a scale relevant to industrial downstream applications. The focus was on the identification of possible environmental key contributors.

The study showed that the off-site production of enzymes under current enzyme product specifications and consumptions is the key contributor to all investigated impacts (GWP, ACP, EP, and POCP) (Fig. 2). This was also observed for the assessment under decreased consumptions. However, with these lowered consumptions, the impact of the enzyme production, and its contribution on the overall impacts decreased

Table 7 Emission data truck transport

Emission	Quantity	References
CO_2	0.06 kg/tkm	NTM (accessed April 6, 2011)
NO_x	0.46 g/tkm	NTM (accessed April 6, 2011)
HC	2.00×10^{-2} g/tkm	NTM (accessed April 6, 2011)
CO	0.13 g/tkm	NTM (accessed April 6, 2011)

significantly from a share of approximately 90 % for the highest consumption, to a share of approximately 60 % under the lowest consumption (Fig. 2). This demonstrates that improvements with regard to consumption of the enzyme product are highly relevant for the environmental performance of wood ethanol-based ethylene using an enzymatic hydrolysis fermentation route.

Another key contributor was the ethanol production (including all steps from pre-processing, fermentation, and distillation). It contributes considerably to the ACP, EP, and POCP of the ethylene life cycle and shows that process design improvements are of relevance for continued research. Moreover, it needs to be considered that our study assessed a process set up for the production of anhydrous ethanol. The latter however, may not be necessary and hydrous ethanol could be of sufficient quality for the production of ethylene. This could lead to energy savings of approximately 5 % in the ethanol production, which would be of relevance especially to the EP and POCP of the ethylene.

The results indicate that enzyme production is the major key contributor, although there appears to be considerable room for improvement with regards to the consumption of the enzyme product. In the consumption scenarios considered in this study impacts decrease by approximately four to six times from the highest to the lowest product consumption. This motivated us to compare our results for enzyme production with results in

Table 6 Inventory ethylene production

|	Quantity	References
Input		
Ethanol	1.74 kg ethanol/kg ethylene	(Kochar et al. 1981; Liptow and Tillman 2009)
Electricity	1.12 MJ_{el}/kg ethylene	(Kochar et al. 1981; Liptow and Tillman 2009)
Internal fuel	3.74 MJ/kg ethylene	(Kochar et al. 1981; Liptow and Tillman 2009)
External fuel	1.68 MJ/kg ethylene	(Kochar et al. 1981; Liptow and Tillman 2009)
Product output		
Ethylene	1 kg	
Process emissions		
CO_2	92.5 g/kg ethylene	(Liptow and Tillman 2012)
NO_x	0.8 g/kg ethylene	(Liptow and Tillman 2012)
SO_2	0.01 g/kg ethylene	(Liptow and Tillman 2012)
HC	8×10^{-5} g/kg ethylene	(Liptow and Tillman 2012)
CO	5×10^{-3} g/kg ethylene	(Liptow and Tillman 2012)
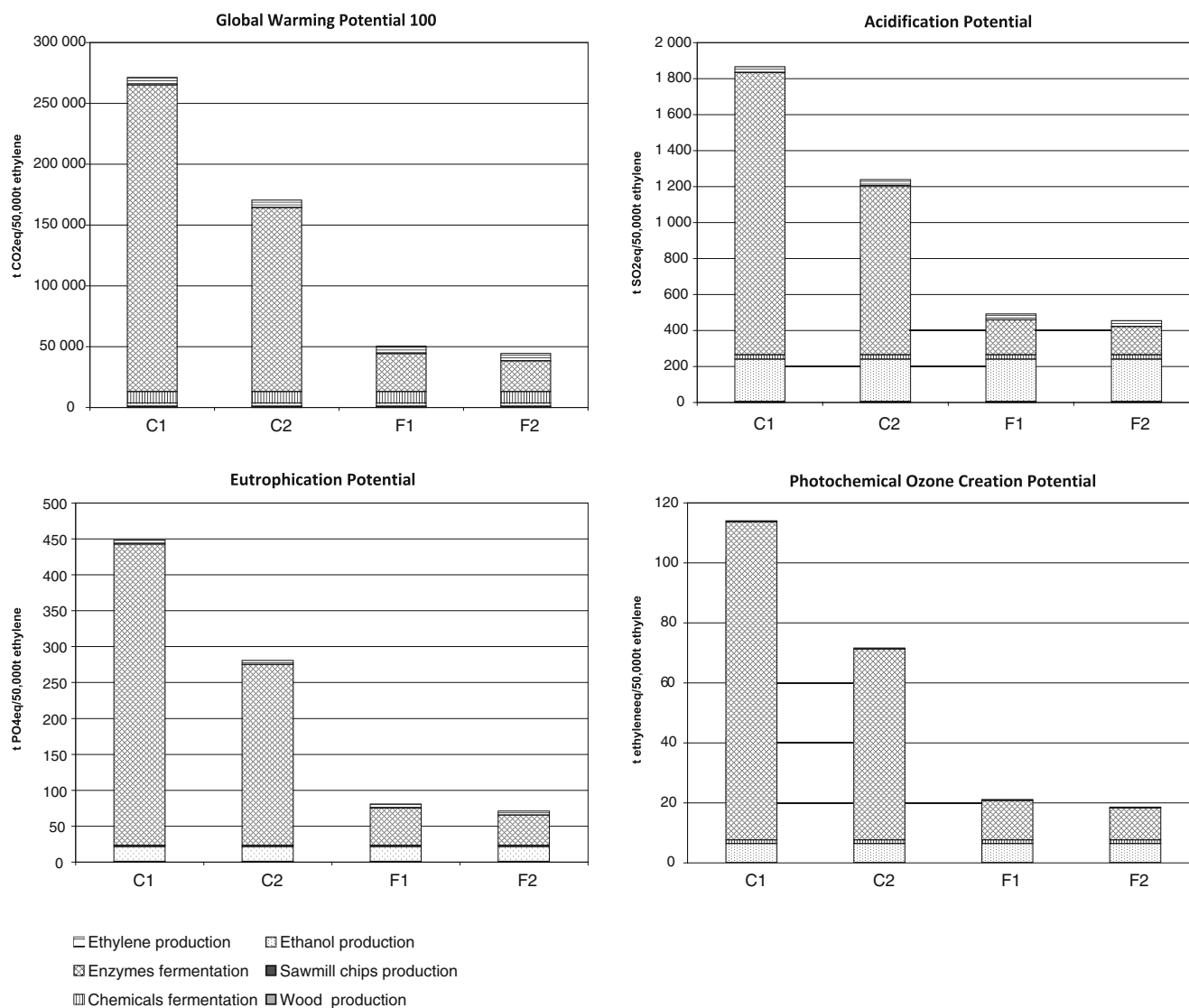
Fig. 2 Impact potentials of sawmill chips based ethylene; *C1* enzyme product consumption with current lower end activity; *C2* enzyme product consumption with current higher end activity; *F1* enzyme product consumption estimated eight times lower than C1; *F2* enzyme product consumption estimated six times lower than C2

literature. Moreover, since our findings could also be of importance for the production of Swedish wood-based ethanol, we compared them with a study for ethanol production based on Swedish willow. In addition we evaluated other process options for the ethanol production process including acid hydrolysis, and alternative pretreatment processes.

3.1 Impact of enzyme production and comparison with ethanol based on Swedish willow

Due to its significant impact, the robustness of the results for the enzyme production is of special importance. For this reason our results were compared to results derived by Slade et al. (2009), who assess the GWP of ethanol production via enzymatic fermentation of spruce chips. Starting with a comparison of the enzyme dosage (FPU/h), the FPU dosage

assessed for our current consumption scenarios (221×10^6 FPU/h) is similar to the dosage used by Slade et al. (2009) (234×10^6 FPU/h). However when comparing the GWP related to enzyme production in these scenarios with Slade et al. (2009), we derive higher GWPs. Only the future lowest consumption scenario has a GWP (0.3 kg CO_2 eq/kg ethanol) comparable to the one reported by Slade et al. (2009) (approximately 11 kg CO_2 eq/GJ ethanol or 0.3 CO_2 eq/kg ethanol). A possible explanation for this could be the difference in data used. While we use data provided by the producer, Slade et al. (2009) derive their impact data by developing their own model. The assumptions and choices of the latter cannot be compared to the ones used by the producer due to lack of detailed information for the producer data. However, despite possible model differences and differences in GWP, also Slade et al. (2009) find that the

production of enzymes contributes significantly to the overall GWP of wood ethanol, supporting our findings. Another finding from the comparison is the need for further investigation into the impact of enzyme production, since data tend to vary considerably between studies. This could also include investigations with regard to real-life production processes, since the latter are under continuous and rapid development, possibly making current assessments, including this study, too conservative.

Since our findings for the key contributors could be of relevance for the production of Swedish wood-based ethanol as well, a comparison with related studies was performed to provide insights on this issue. We compared our key contributors with the ones identified in a recent study of González-García et al. (2012). They assess the production of Swedish ethanol for E85 (85 % (v/v) ethanol) from short rotation willow, using electricity data for the Swedish national electricity grid and allocating based on economic value, which is very similar to the choices applied in our study. However in contrast, they assess the production of enzymes as on-site, and use data adopted from Aden et al. (2002) for the ethanol production process.

González-García et al. (2012) find that the on-site production of enzymes is a relevant contributor to the GWP. This shows that not only under off-site, as assessed in our study, but also under on-site production enzymes is of importance and could play a considerable role in the environmental impact of Swedish wood ethanol. A further key contributor to GWP, POCP and ACP as reported by González-García et al. (2012) is the ethanol production. While we have similar results for the ACP and POCP, ethanol production has no significant impact on our GWP. This difference between the studies is due to the different approach for the carbon uptake and release by biomass. González-García et al. (2012) account for the carbon released from the combustion of biomass-based by-products and wastes during ethanol production while also accounting for the carbon uptake during the biomass growth. In contrast, we do neither account for the uptake nor the release of carbon from biomass, which overall will lead to the same net GWP when comparing to the approach applied by González-García et al. (2012). However, with regard to key contributors the choice of approach can be of importance and reveal additional hot spots.

Another difference in key contributors is the impact of the forestry phase. González-García et al. (2012) find that the willow production phase (forestry phase) is of major importance to almost all investigated impacts. However, we found that forestry activities have no considerable part in our findings, which is based on the fact that the woody feedstock assessed is a by-product and not dedicated wood as investigated by González-García et al. (2012). The result is a small share of the feedstock on the environmental burdens caused by the forestry phase. Nevertheless, the difference reveals the influence of the biomass choice on the key contributors, which could be of importance when choosing feedstocks and improvement measures.

3.2 Acid hydrolysis and pretreatment alternatives

The assessed route, via enzymatic hydrolysis, is currently in the focus of Swedish research efforts. However, there are also other hydrolysis options such as concentrated acid and dilute acid hydrolysis. With regard to the latter, Slade et al. (2009) show that dilute acid hydrolysis has a lower GWP than the enzymatic process. However, the costs for this process are not to be underestimated since corrosive-resistant equipment is needed (Galbe et al. 2007) and ethanol yields are low due the formation of toxic compounds (Galbe and Zacchi 2007; Verardi et al. 2011; Wesolowski 2005). The latter are less of an issue for the concentrated acid hydrolysis that shows higher ethanol yield (Wesolowski 2005). However, the corrosive effect of the acid and its energy-intensive recovery (Jeihanipour 2011) again lead to considerable cost estimates in the literature. Concerning the environmental impact of the concentrated acid process, no literature was found to make a direct comparison with the enzymatic process. Nevertheless, Uihlien et al. (2009) show that the production of the acid has a significant share on the environmental impact of the ethanol production.

Apart from the hydrolysis, another important process during the conversion from biomass to ethanol is the pretreatment, which serves to break the structure of the lignocellulosic biomass and to make it accessible to the hydrolyzing agent (Huang et al. 2011). In this study, steam pretreatment was assessed. However, there are also other methods such as ammonia fiber explosion (AFEX), ionic liquid (IL) and organosolv pretreatment. Since these processes are at different stages of maturity, data regarding their environmental impact are available to a different extent. For example, Lui et al. (2012) just recently stated that for the IL process further investigations with regard to its environmental impact are needed. Lack of assessments is also an issue for the organosolv process. However, energy-intensive recovery of the cost-intensive solvents used in some variations of the process (Zhao et al. 2009) might influence the environmental impact of the organosolv pretreatment considerably. With regard to the environmental impact of AFEX pretreatment, MacLean et al. (2009) found that the global warming impact of switch grass ethanol produced with AFEX is comparable to a dilute acid pretreatment route (total GWP AFEX 27 g CO_2 eq/MJ ethanol; total GWP dilute acid pretreatment 29 g CO_2 eq/MJ ethanol). Moreover, they found that ammonia is a major contributor to the AFEX route's total GWP. This could become of special relevance for woody materials, since they require high ammonia loads in order to degrade (Bals et al. 2011).

4 Conclusions

The study has shown that the production of the enzymes used for the hydrolysis of the sawmill chips is decisive for the environmental impact of the wood-based ethylene. However, its contribution to the overall environmental impact would be significantly lowered if improvements were accomplished with regard to consumption (e.g., by improved product properties) and/or environmentally improved production processes. This makes further developments in this direction desirable and enzyme producers are already heading into this direction.

In addition to the enzymatic hydrolysis, other process options may also be considered. Literature, though scarce, suggests that hydrolysis with dilute acid can be environmentally preferable when compared to enzymatic hydrolysis. However, since this is based on only one study, further confirmation is needed.

Furthermore, the scarcity of environmental assessments is also an issue for other pretreatment methods, and their environmental impact. This is mainly due to their high energy demanding recovery processes, which may only be estimated for industrial scale volumes.

Also worth further investigations would be the ethanol production process. For instance, production of ethylene from ethanol does not necessarily require anhydrous ethanol, and the use of ethanol with a lower purity level would lead to recognizable energy savings, and lower environmental impacts.

Another point of interest for future investigations is the question of production scale under local feedstock supply. This study assessed a scale accounting for approximately 8 % of the total Swedish ethylene production. However, in the end, issues such as decreased availability of fossil resources, and competition for biomass will influence the need for large volume biomass alternatives. This could introduce additional environmental issues not detectable in small-scale scenarios. In addition, a further aspect worth considering when investigating feedstock supply is the difference in impact between items such as wood residues and dedicated wood, since it could influence the overall impact of the ethylene or other products considerably.

References

Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, Wallace B (2002) Montague L, Slayton A, Lukas J (Harris Group, Seattle, Washington). Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid hydrolysis and enzymatic hydrolysis for corn stover. NREL/TP-510-32438, National Renewable Energy Lab

Andersson B-I (1996) Miljö- och energidatabas för träindustrin - etapp I (Environmental and energy data for the forestry industry—stage I) Rapport P 9601006. Trätek - Institutet för Träteknisk Forskning, Stockholm

Bals B, Wedding C, Balan V, Sendich E, Dale B (2011) Evaluating the impact of ammonia fiber expansion (AFEX) pretreatment conditions on the cost of ethanol production. Biores Technol 102(2):1277–1283

Barrocas HV, Lacerda A (2007) Process for the production of ethylene from ethyl alcohol. Brazil Patent

Barta Z, Kovacs K, Reczey K, Zacchi G (2010a) Process design and economics of on-site cellulase production on various carbon sources in a softwood-based ethanol plant. Enzyme Res. doi:10.4061/2010/734182

Barta Z, Reczey K, Zacchi G (2010b) Techno-economic evaluation of stillage treatment with anaerobic digestion in a softwood-to-ethanol process. Biotechnol Biofuels 3(1):1–11

Berg S, Lindholm EL (2005) Energy use and environmental impacts of forest operations in Sweden. J Clean Prod 13(1):33–42

Börjesson P, Tufvesson L, Lantz M (2010) Life cycle assessment of biofuels in Sweden Report no 70

Braskem (accessed September 11, 2011) Green ethylene. http://www.braskem.com.br/plasticoverde/eng/linha_tempo.html

E-On (accessed March 7, 2011) Priser (prices). http://www.eon.se/templates/Eon2TextPageaspx?id=47699&epslanguage=SV&redirect=1#

Ferreira SMP, Duarte AP, Queiroz JA, Domingues FC (2009) Influence of buffer systems on Trichoderma reesei Rut C-30 morphology and cellulase production. Electron J Biotechnol 12(3):8–9

Galbe M, Zacchi G (2007) Pretreatment of lignocellulosic materials for efficient bioethanol production. Adv Biochem Eng Biotechnol 108:41–65

Galbe M, Sassner P, Wingren A, Zacchi G (2007) Process engineering economics of bioethanol production. In: Springer-Verlag (ed)

Gao Y, Skutsch M, Drigo R, Pacheco P, Masera O (2011) Assessing deforestation from biofuels: methodological challenges. Appl Geogr 31(2):508–518

González-García S, Berg S, Feijoo G, Moreira MT (2009) Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. Int J Life Cycle Assess 14(4):340–353

González-García S, Mola-Yudego B, Murphy RJ (2012) Life cycle assessment of potential energy uses for short rotation willow biomass in Sweden. Int J Life Cycle Assess. doi:10.1007/s11367-012-0536-2

Gottschlich N (2004) Nachhaltigkeitsbewertung eines biologisch abbaubaren Kunststoffes unter gleichzeitiger Erarbeitung von Maßnahmenkatalogen. Fachhochschule Lippe und Höxter, Höxter

Huang R, Su R, Qi W, He Z (2011) Bioconversion of lignocellulose into bioethanol: process intensification and mechanism research. Bioenergy Res 4(4):225–245

International Energy Agency (2008) Energy policies of IEA countries Sweden 2008 Review

International Energy Agency (IEA) (2011) World key energy statistics

ISO (2006) International Organization for Standardization: ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework. ISO, Geneva, Switzerland

Jeihanipour A (2011) Waste textiles bioprocessing to ethanol and biogas. Chalmers University of Technology, Göteborg

Kochar N, Merims R, Padia A (1981) Ethylene from ethanol. CEP (June):66–71

Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C, Priess JA (2010) Indirect land-use changes can overcome carbon savings from biofuels in Brazil. Proc Natl Acad Sci 107(8):3388–3393

Lehtikangas P (1999) Lagringshandbok för trädbränslen slu. Sveriges lantbruksuniversitet, Uppsala

Lindholm EL (2006) Energy use in Swedish forestry and its environmental impact. SLU (Sveriges lantbruksuniversitet), Uppsala

Liptow C, Tillman AM (2009) Comparative life cycle assessment of polyethylene based on sugarcane and crude oil; internal report. Chalmers University of Technology, Göteborg

Liptow C, Tillman A-M (2012) A comparative LCA study of polyethylene based on sugarcane and crude oil. JIE 16(3):420–435

Liu QP, Hou XD, Li N, Zong MH (2012) Ionic liquids from renewable biomaterials: synthesis, characterization and application in the pretreatment of biomass. Green Chem 14(2):304–307

MacLean HL, Spatari S (2009) The contribution of enzymes and process chemicals to the life cycle of ethanol. Environ Res Lett 4:014001

Naturvårdsverket Swedish EPA (2010) Sågverk Fakta om branschen och dess miljöpåverkan branschfakta utgåva 1, April 2010 (Sawmill—facts from the industry and its environmental impact) branschfakta utgåva 1, April 2010. Naturvårdsverket, Stockholm

Naumann K (2011) Abschlussworkshop Monitoring zur Wirkung nationaler und internationaler gesetzlicher Rahmenbedingungen auf die Marktentwicklung im Biokraftstoffsektor Deutsches Biomasse Forschungs Zentrum

Nordfjell T, Nilsson P, Henningsson M, Wästerlund I (2008) Unutilized biomass resources in Swedish young dense forests. Paper presented at the World Bioenergy

Novozymes (2012) http://bioenergy.novozymes.com/en/cellulosic-ethanol/CellicCTec3/product-description/Pages/default.aspx, accessed February 23, 2012

Network for Transport and the Environment (NTM) (2011) http://www.ntmcalc.se/index.html

PRé Consultants SimaPro 7.2. Amersfoort, The Netherlands, accessed April 6, 2011

Sassner P, Galbe M, Zacchi G (2008) Techno-economic evaluation of bioethanol production from three different lignocellulosic materials. Biomass Bioenergy 32(5):422–430

SEKAB (2012) World Leading in the production of ethanol from cellulose. http://www.sekab.com/cellulose-ethanol/demo-plant, accessed March 26, 2012

Skogsstyrelsen (2010) Swedish Statistical yearbook of forestry 2010. Skogsstyrelsen

Slade R, Bauen A, Shah N (2009) The greenhouse gas emissions performance of cellulosic ethanol supply chains in Europe. Biotechnol Biofuels 2(15):1–19

Statistics Sweden (2011) Electricity prices for different customers. http://www.scb.se/Pages/TableAndChart____85467aspx, accessed March 7, 2011

Svensk Fjärrvärme (Swedish district heating) (2011) Fjärrvärmepriser (prices for district heating). http://www.svenskfjarrvarme.se/Statistik–Pris/Fjarrvarmepriser/, accessed March 7, 2011

Swedish Forest Industries Federation (2010) The Swedish forest industries: facts and figures 2009. Swedish Forest Industries Federation, Stockholm, Sweden

Tillman A-M (2000) Significance of decision-making for LCA methodology. Environ Impact Assess Rev 20(1):113–123

Uihlein A, Schebek L (2009) Environmental impacts of a lignocellulose feedstock biorefinery system: An assessment. Biomass Bioenergy 33(5):793–802

Verardi A, De Bari I, Ricca E, Calabro V (2011) Hydrolysis of lignocellulosic biomass: current status of processes and technologies and future perspectives. Bioethanol, pp 95–122

Wesolowski D (2005) The sustainability of ethanol fuel in the United States

Zhao X, Cheng K, Liu D (2009) Organosolv pretreatment of lignocellulosic biomass for enzymatic hydrolysis. Appl Microbiol Biotechnol 82(5):815–827